New Approach to Voltage/Reactive Power Management for PJM System

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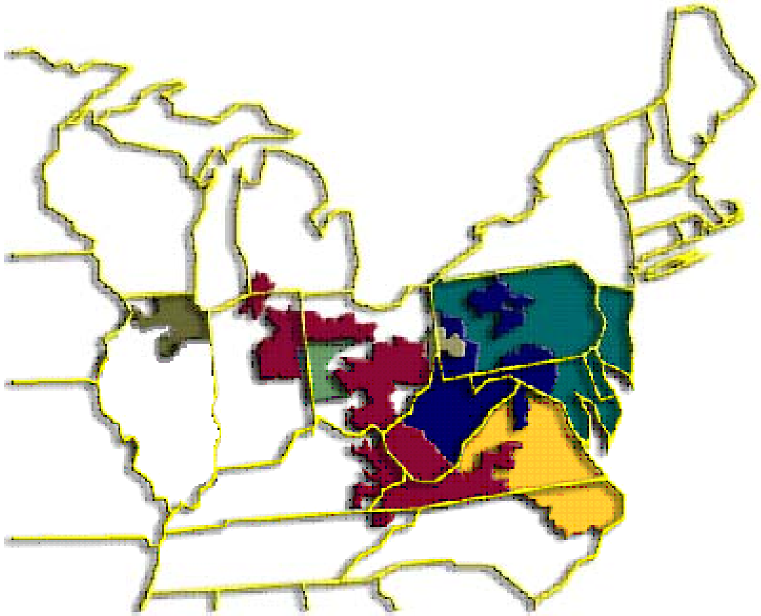
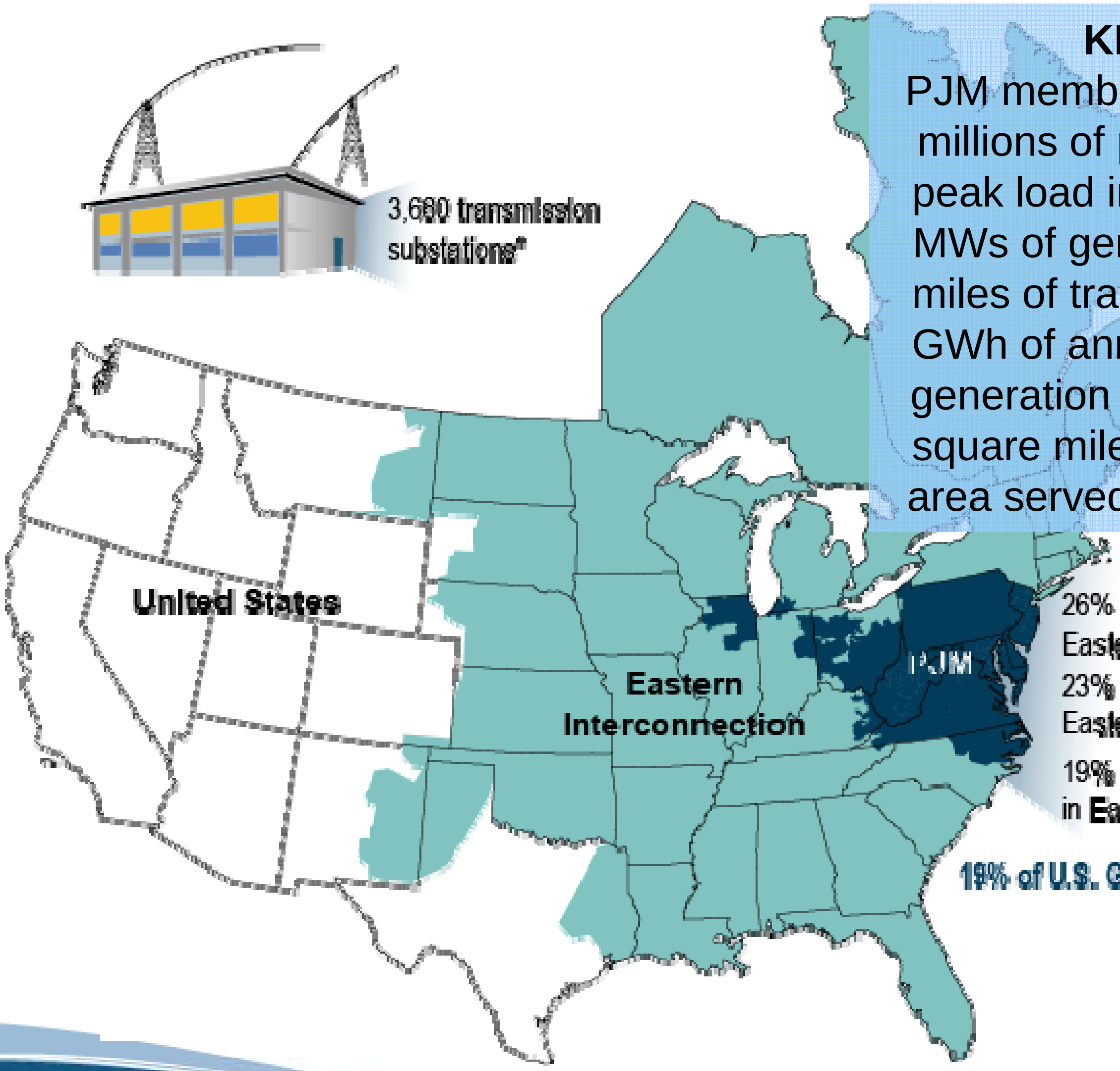
PJM’s Service Territory



- 🟩 PJM
- 🟦 PJM West
- ⬜ Duquesne
- 🟥 AEP
- 🟩 Dayton Power & Light
- 🟫 ComEd
- 🟨 Dominion Power

PJM as Part of the Eastern Interconnection



3,680 transmission substations*

KEY STATISTICS	
PJM member companies	400+
millions of people served	51
peak load in megawatts	145,000
MWs of generating capacity	165,738
miles of transmission lines	56,070
GWh of annual energy	700,000
generation sources	1,082
square miles of territory	164,260
area served	13 states + DC

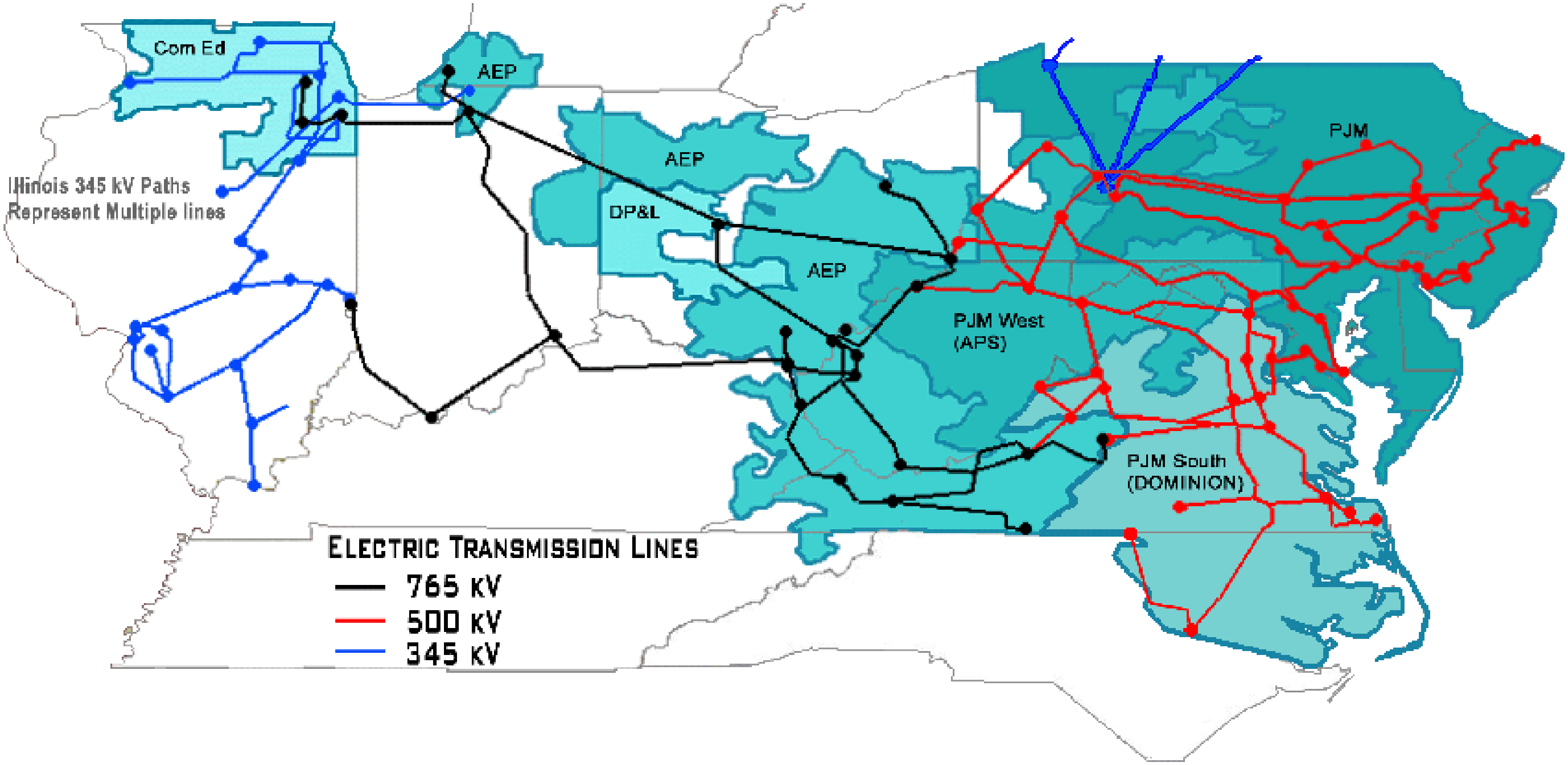
26% of generation in Eastern Interconnection*

23% of load in Eastern Interconnection*

19% of transmission assets in Eastern Interconnection*

19% of U.S. GDP produced in PJM*

Backbone Transmission System



Modeling Detail

The level of modeling detail required depends on the facilities that Security Analysis is required to evaluate.

- 765 kV
- 500 kV
- 345 kV
- 230 kV
- 138 kV
- 115 kV
- 69 kV & below - depending on detail required

Network Model in PJM EMS

Node:	75,154
Bus:	13,548
Unit:	2459
CB:	59693
XF:	5463
Line:	11,805
Shunt:	2540

Purpose --- Voltage /Reactive Power Control

1. To control the system voltage profile to meet the customer requirements --- (Voltage Quality)

2. To control the power flow in the system to an optimal level to reduce losses --- (Energy Efficiency)

3. To control the reserve of reactive power to ensure its sufficiency during normal and emergency conditions to prevent voltage collapse (instability) --- (System Security)

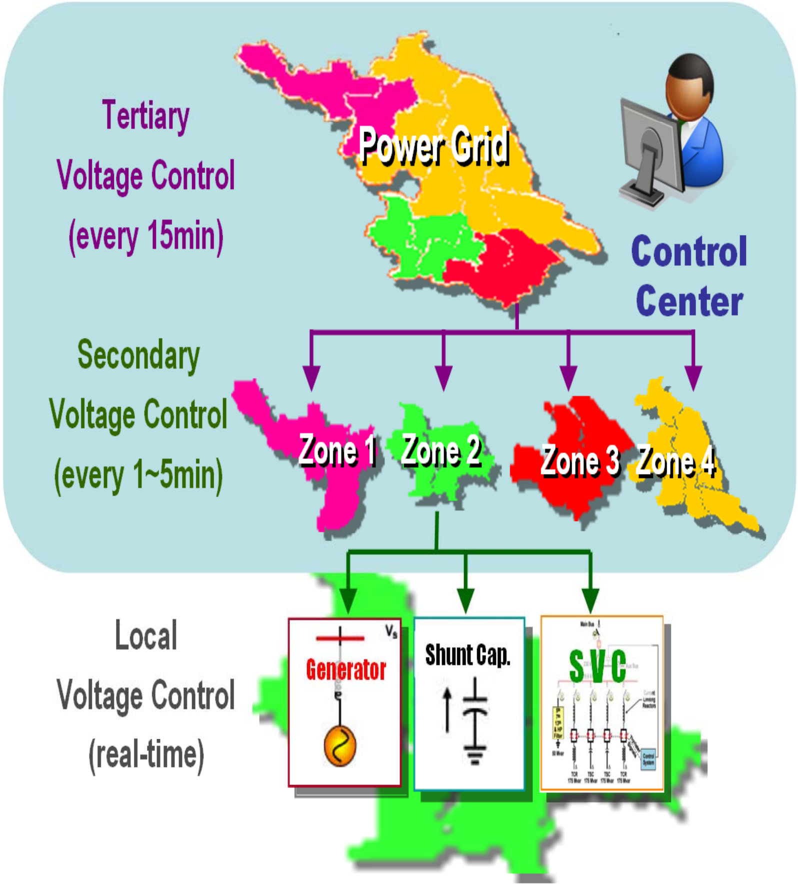
Current approach of determination of the voltage schedule in PJM system:

1. Each TO determines their own area voltage schedule based on their Power Study and experiences. If TO has no voltage schedule for the area, PJM offer a default voltage schedule.
2. This approach lacks of system-wide coordination to determine PJM system voltage schedule.
3. Potentially, violation of voltage occurred frequently and unexpected massive flow of reactive power (leads to depress the level of security and economy)

Optimal Dynamic Voltage Control System (AVC):

1. Determine voltage schedule and Var control system-wide
2. Combine optimization and traditional approach (rule based)
3. Achieve the objective of minimum of system loss, or maximum of MW transfer
4. Improve system voltage profile, real time security and reliability .

Optimal Dynamic Voltage Control System ---Two Levels of Optimizations



1. TVC is the tertiary voltage control level, responsible for economy (reduction in system loss), and is a slow control. TVC is a optimal solution to set the voltage setting (Vp1 to Vpn) for the pilot (key) buses in the system.

2. SVC is the secondary voltage control level, responsible for quality and security, and is a fast control. SVC is a optimal solution to set voltage schedule (Vg) for each generator in the system.

• Objective

$$\min \ f = P_{Loss} = \sum_{(i,j)\in NL} (P_{ij} + P_{ji})$$

- **Power flow constraints**

$$h(x) = \begin{cases} P_{Gi} - P_{Di} - V_i \sum_{j\in I} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) - V_i^2 G_{ii} = 0 \\ Q_{Gi} - Q_{Di} - V_i \sum_{j\in I} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) + V_i^2 B_{ii} = 0 \\ i = 1,\cdots,NB \qquad \theta_s = 0 \end{cases}$$

- **Operational limits**

$$Q_{Gi\min} \le Q_{Gi} \le Q_{Gi\max} \qquad i = 1,\cdots,NQG$$

$$V_{i\min} \le V_i \le V_{i\max} \qquad i = 1,\cdots,NB$$

$$t_{k\min} \le t_k \le t_{k\max} \qquad k = 1,\cdots,NT$$

$$\max(|I_{ij}|,|I_{ji}|) \le I_{ij\max} \qquad (i,j) \in NL$$

- **Objective**

$$\min\{W_p \left\|\alpha \cdot \Delta V_p + C_g \cdot \Delta Q_g\right\|^2 + W_q \left\|\Theta_g\right\|^2\}$$

$$\text{W here}\quad \Theta_{g_i} = \frac{Q_{g_i} + \Delta Q_{g_i} - Q_{g_i}^{\min}}{Q_{g_i}^{\max} - Q_{g_i}^{\min}}$$

- **constraints**

$$\left\|C_{vg} \cdot \Delta Q_g\right\| \le \Delta V_{gmx}$$

$$V_{gmn} \le V_g + C_{vg} \cdot \Delta Q_g \le V_{gmx}$$

$$V_{pmn} \le V_p + C_g \cdot \Delta Q_g \le V_{pmx}$$

$$Q_{gmn} \le Q_g + \Delta Q_g \le Q_{gmx}$$

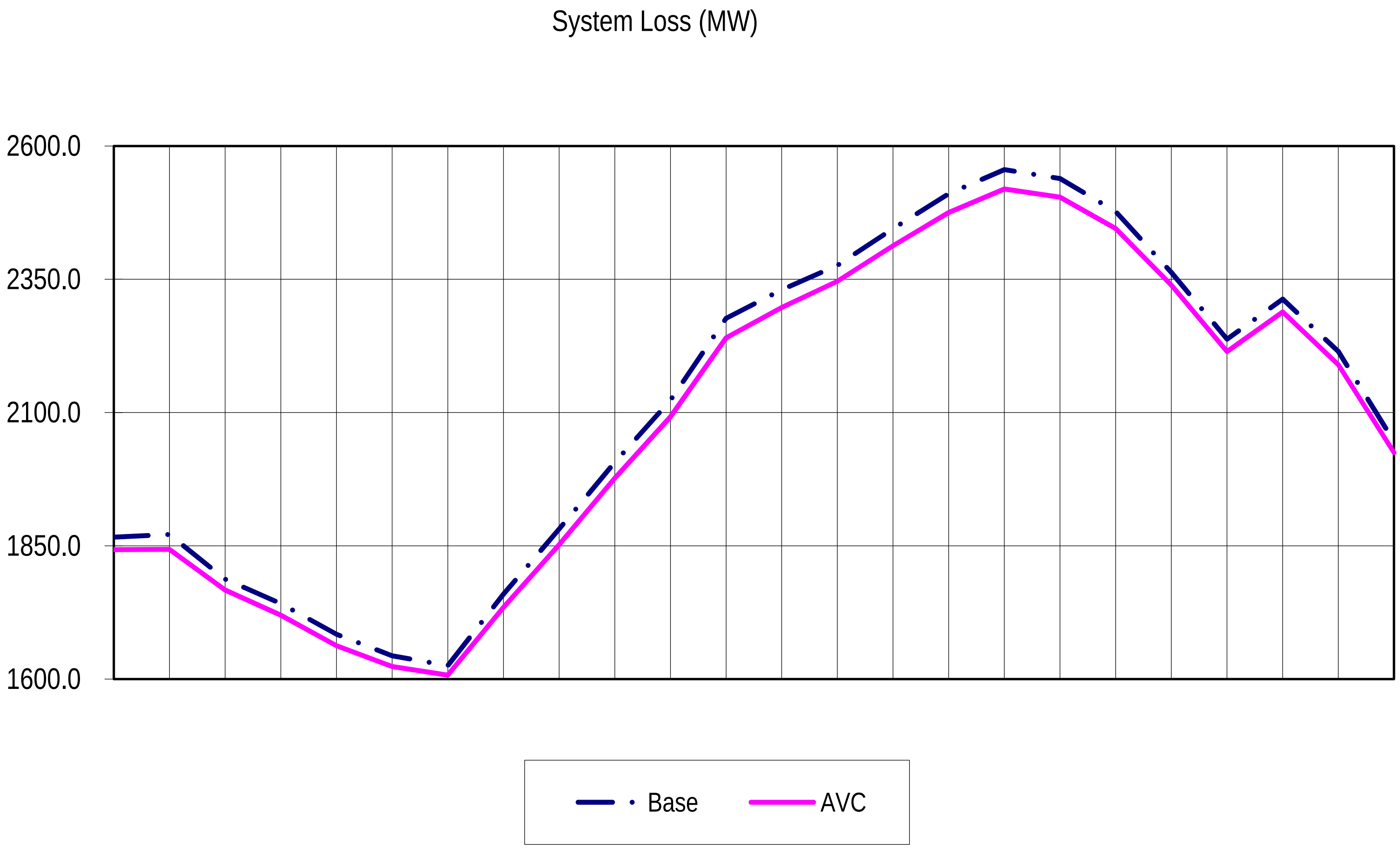
$$\Delta V_{gmx} : MaxAdjustForHighVoltageOfPlantInAStep$$

$$V_{gmn}, V_{gmx} : \lim itsOfHighVoltageOfPlant$$

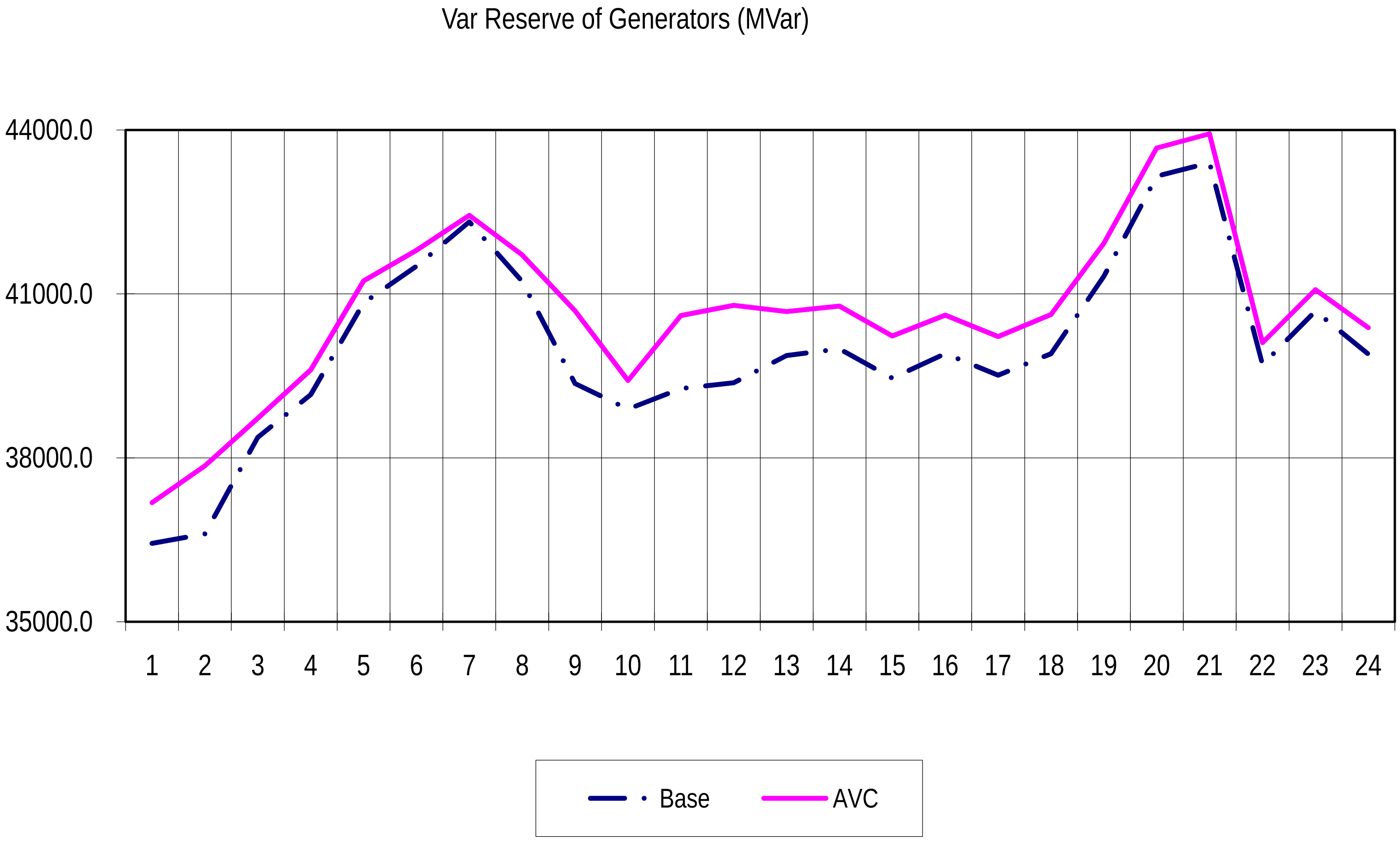
$$V_{pmn}, V_{pmx} : \lim itsOfPilotBusVoltage$$

$$C_{vg} : SensitivityOfHighVoltageWith\,\mathrm{Re}\,spectTo\,\mathrm{Re}\,activeOutput$$

June 26 – 24 Hours



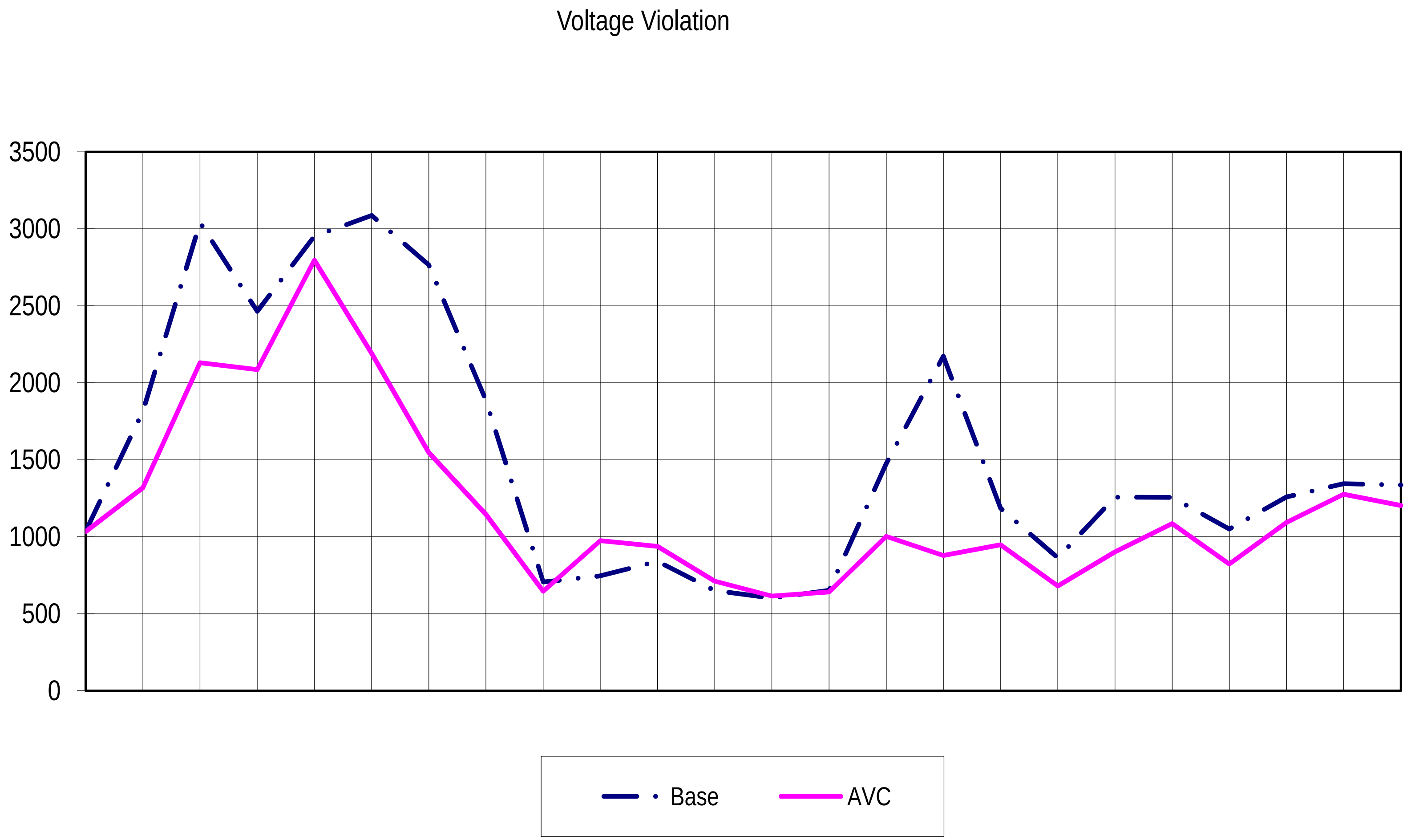
June 26 – 24 Hours



June 26 – 24 Hours

Snapshot	Loss				Var Reserve			
Snapshot	Base	AVC	Reduction	Rate	Base	AVC	Increase	Rate
100626_0004	1866.4	1842.8	23.6	1.26%	36434.5	37179.5	745.0	2.04%
100626_0103	1871.4	1843.3	28.1	1.50%	36608.1	37853.3	1245.2	3.40%
100626_0202	1787.5	1767.1	20.4	1.14%	38374.7	38724.1	349.4	0.91%
100626_0302	1741.8	1720.1	21.7	1.25%	39156.4	39610.2	453.8	1.16%
100626_0404	1684.4	1662.7	21.7	1.29%	40837.9	41236.7	398.8	0.98%
100626_0502	1643.7	1623.6	20.1	1.22%	41505.6	41797.1	291.5	0.70%
100626_0607	1625.4	1607.5	17.9	1.10%	42318.3	42437.1	118.8	0.28%
100626_0703	1759.2	1734.5	24.7	1.40%	41230.6	41713.4	482.8	1.17%
100626_0802	1881.5	1852.0	29.5	1.57%	39362.0	40691.5	1329.5	3.38%
100626_0903	2006.4	1976.9	29.5	1.47%	38891.0	39414.8	523.8	1.35%
100626_1003	2122.8	2092.0	30.8	1.45%	39269.3	40604.4	1335.1	3.40%
100626_1103	2276.7	2240.3	36.4	1.60%	39374.8	40789.3	1414.5	3.59%
100626_1201	2330.3	2297.1	33.2	1.42%	39871.8	40674.9	803.1	2.01%
100626_1300	2376.3	2346.3	30.0	1.26%	39994.4	40775.3	780.9	1.95%
100626_1403	2445.1	2413.0	32.1	1.31%	39457.0	40229.9	772.9	1.96%
100626_1500	2510.6	2475.2	35.4	1.41%	39906.9	40610.5	703.6	1.76%
100626_1602	2555.7	2519.4	36.3	1.42%	39512.3	40217.3	705.0	1.78%
100626_1704	2538.9	2504.1	34.8	1.37%	39905.3	40621.0	715.7	1.79%
100626_1804	2476.9	2445.1	31.8	1.28%	41322.5	41925.5	603.0	1.46%
100626_1906	2362.7	2338.9	23.8	1.01%	43153.1	43668.1	515.0	1.19%
100626_2000	2237.6	2214.4	23.2	1.04%	43403.2	43929.1	525.9	1.21%
100626_2104	2312.9	2288.8	24.1	1.04%	39705.3	40108.3	403.0	1.01%
100626_2202	2214.5	2189.6	24.9	1.12%	40686.6	41078.0	391.4	0.96%
100626_2304	2045.7	2025.0	20.7	1.01%	39900.6	40381.3	480.7	1.20%
				1.29%				1.69%

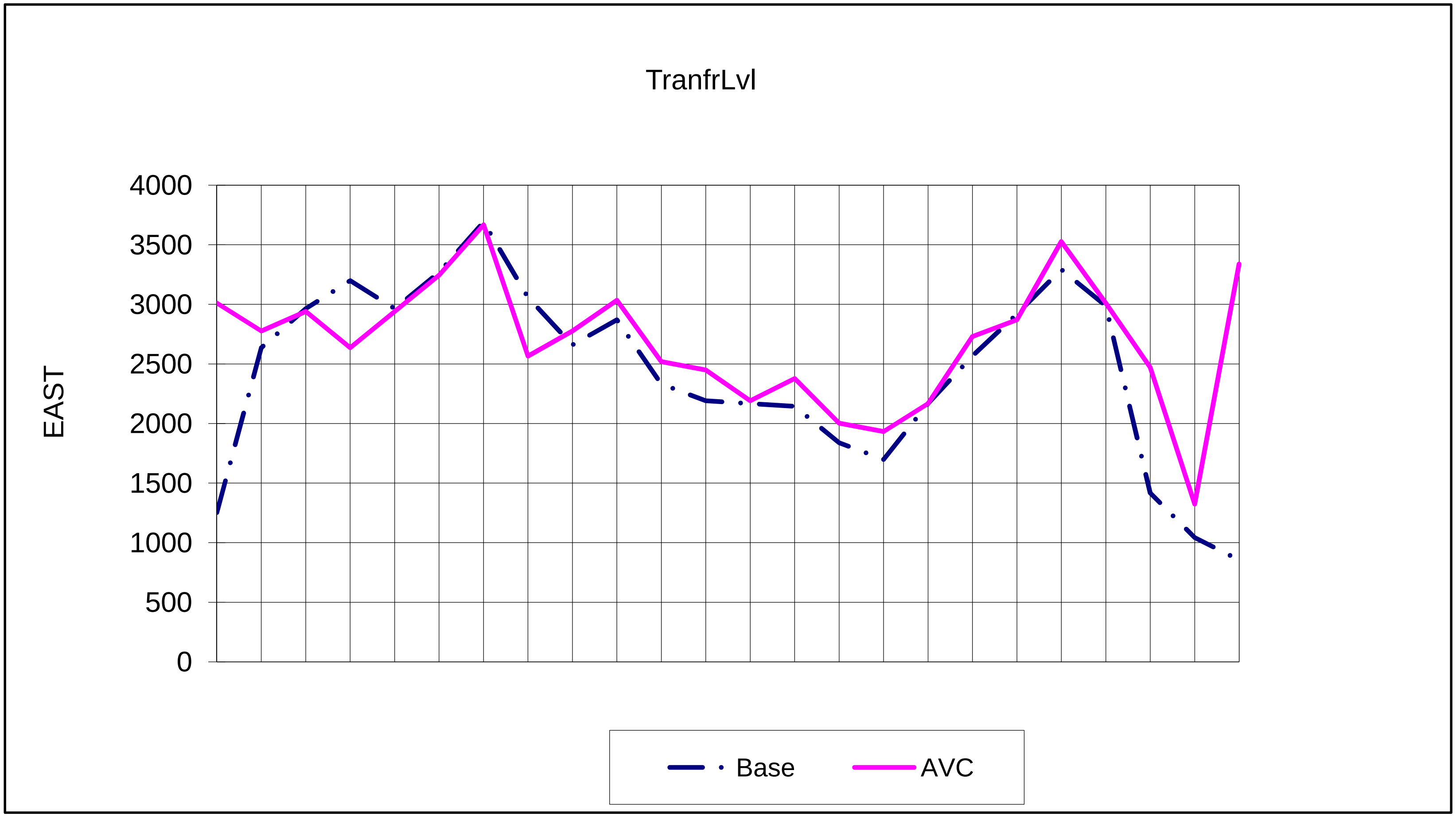
June 26 – 24 Hours



June 26 – 24 Hours

Snapshot	Base	AVC
100626_0004	1037	1034
100626_0103	1817	1319
100626_0202	3041	2130
100626_0302	2464	2086
100626_0404	2952	2796
100626_0502	3087	2191
100626_0607	2766	1547
100626_0703	1885	1145
100626_0802	707	646
100626_0903	746	975
100626_1003	841	938
100626_1103	651	712
100626_1201	602	615
100626_1300	652	642
100626_1403	1475	1003
100626_1500	2173	879
100626_1602	1186	948
100626_1704	863	681
100626_1804	1257	902
100626_1906	1256	1086
100626_2000	1051	823
100626_2104	1259	1093
100626_2202	1345	1276
100626_2304	1337	1203

June 26 – 24 Hours Voltage Stability Limits



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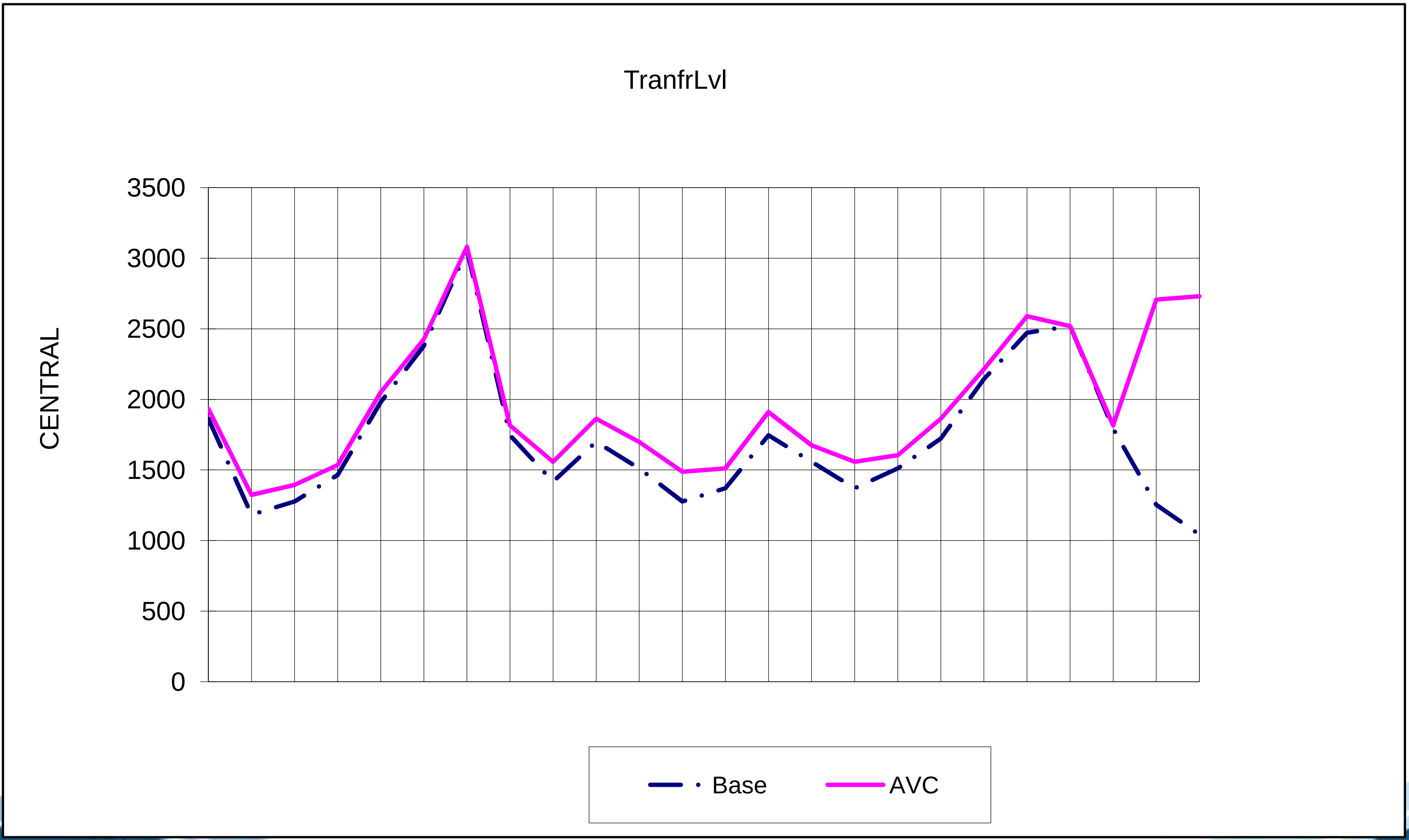

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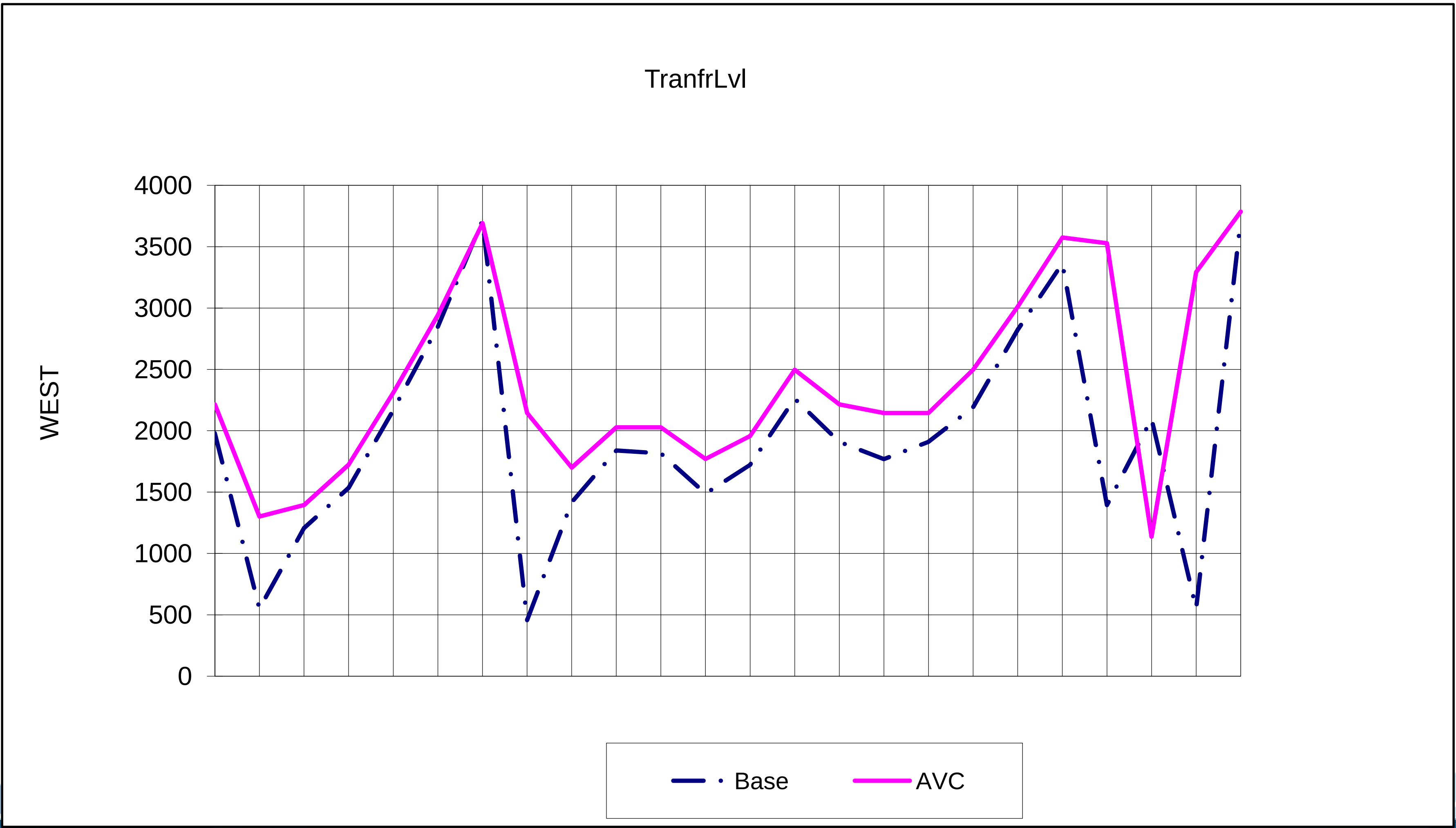

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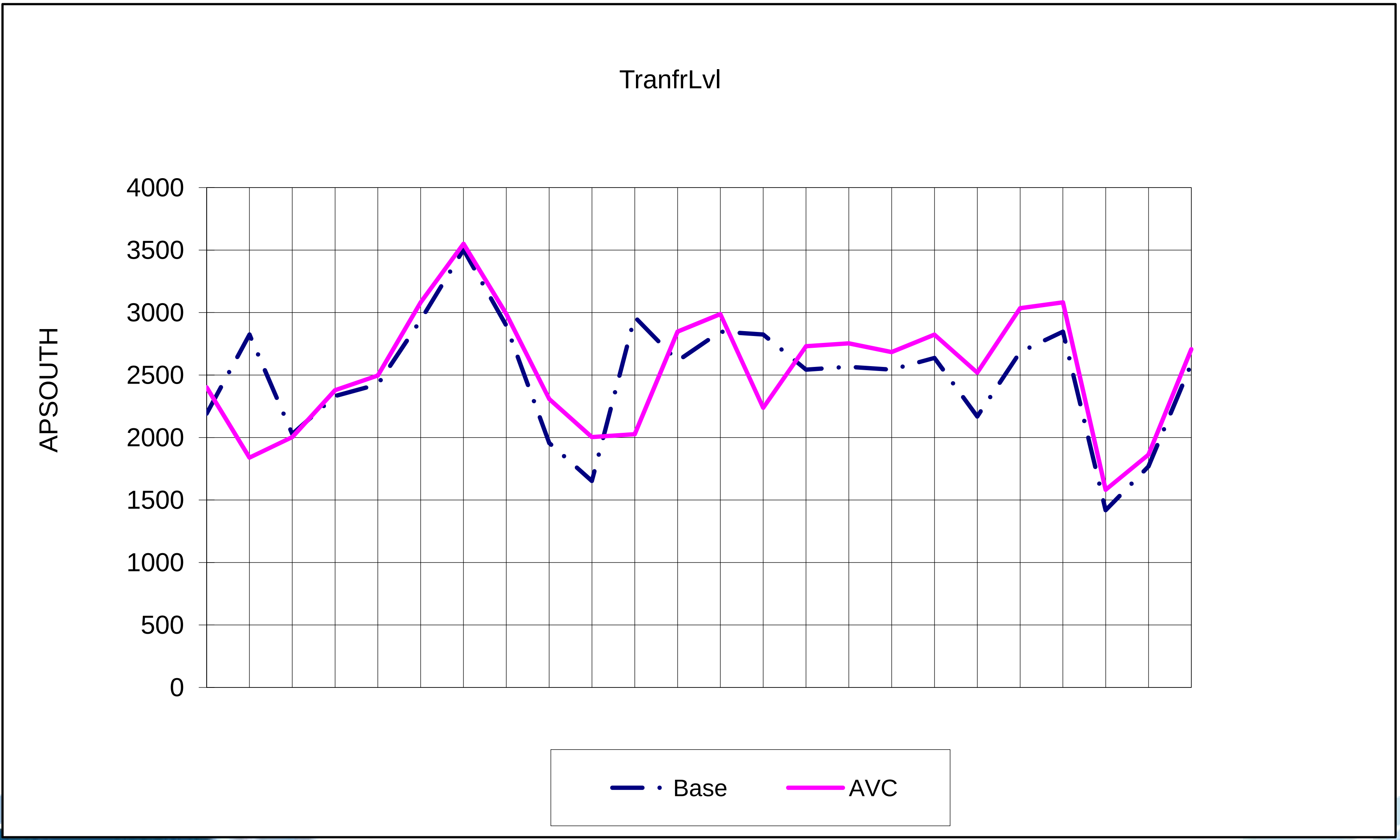

Conclusions – Phase I Evaluation

1. Average reduction of transmission system loss: 1.29 %
   - For the example of day of June 26, 27.3MW, Save energy about 239 million kWh/year
   - If electricity rate is $0.08/kWh, Save money: $ 19.13 million/year

2. Average increase of system MVAR reserve: about 1.69 %

3. Improved system security for pre-contingency and post-contingency

   - Voltage Stability limits

Current Status /Next Steps

1. Phase 2 is the on-line evaluation of AVC system on PJM real time test system
   - Optimization objectives
     - ➢Minimizing power system losses
     - ➢Increase Var reserve of generators
     - ➢Improve system voltage profile.
   - OPF (Optimal Power Flow) + Contingency Analysis (CA)
     - ➢OPF and CA tools adopted to consider performance under contingencies.
   - Discrete control
     - ➢Capacitors and reactors can be taken into optimization together with generators to increase Var reserve further.
   - •Provide new set of optimal voltage schedule every hour

2. Phase 3 will be the production of AVC system